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Study of Microstructure, Texture, and Cooking Qualities of Reformulated Whole Wheat Flour Pasta by Substituting Water with Stearic Acid–Candelilla Wax–Groundnut Oil Oleogel

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Abstract: Oleogels, which are traditionally utilized to reduce saturated and trans fats in bakery foods, have recently shown promising applications in non-bakery foods, particularly in the enhancement of their food texture and cooking qualities. This study investigates the impact of incorporating stearic acid-containing candelilla wax–groundnut oil oleogel in various proportions on the production of whole wheat pasta. Five different pasta samples were prepared by replacing water with oleogels in varying concentrations (2.5%, 5%, 10%, and 15%), and their physicochemical attributes were evaluated using a range of analytical methods for both cooked and uncooked pasta (like microscopy, colorimetry, dimensional analysis, texture, cooking qualities, moisture content, and FTIR). Significant differences in width, thickness, and color properties were observed between the control sample (0% oleogel) and those containing oleogel, with notable variations in surface texture and color intensities, particularly with the higher oleogel content ($p < 0.05$). Cooked pasta exhibited lower L* values and higher a* values than uncooked pasta. Stereo zoom microscope and field emission scanning electron microscope (FESEM) micrographs demonstrated a change in the pasta surface topology and microstructures. Dark spots on the pasta with greater oleogel concentrations (samples with 10% and 15% oleogel replacement) suggest the formation of starch–lipid complexes. Cooking induced pore formation, which was more pronounced when the oleogel content was increased, impacted the water absorption capacity, swelling index, and moisture content. The cooked samples exhibited higher moisture content and improved polymer network stability compared to the uncooked ones, indicating the potential of oleogel incorporation to modulate pasta properties in a concentration-dependent manner. These findings underscore the versatility of oleogels when their applications are diversified in non-bakery foods to enhance food texture and quality.

Keywords: oleogel; whole wheat flour pasta; starch–lipid complex; surface topology; cooking quality

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1. Introduction

The rising interest in healthy food products in recent years has been driven by sedentary and fast-paced lifestyles as well as increased awareness of the importance of a healthy diet. Consumers are increasingly demanding food products that are low in calories and contain reduced levels of unhealthy saturated and trans fats, which are associated with a higher risk of cardiac disease, type 2 diabetes, and cancers. To meet this demand, several technological advancements have been made in the field of food science through

the incorporation of healthy additives. One such advancement is the introduction of the oleogel system, which has resulted in a breakthrough that has effectively reduced the levels of saturated and trans fats in food products [1–3] without compromising the food textural properties [3] and mouthfeel. Oleogels are semi-solid fat systems with defining characteristics, such as edibility, low gelling concentration, and restricted oil migration. In recent years, oleogels have gained considerable attention in the formulation of bakery foods, such as cakes [4], biscuits [5], and, cookies [6], as well as other food products, such as spreads [7], ice cream [8], and chocolates [9], where they have successfully replaced the traditional solid fats, like butter or margarine. Emulsifiers have also been added to oleogels to enhance and modulate their properties, e.g., in terms of texture, crystallinity, and thermal behavior [10–12].

Pasta is a staple food that is typically made by combining wheat flour and water and, subsequently, subjecting it to extrusion to obtain the desired shape and texture [13]. It is widely consumed all over the world due to its taste, convenience of preparation, and affordability. Pasta also provides health benefits as it is low in calories and has a low glycemic index owing to its high resistant starch content, which also helps to reduce blood glucose levels [14]. Generally, pasta is a rich source of complex carbohydrates, but it is low in sodium, fats, cholesterol, and other essential nutrients, like proteins, vitamins, iron, and minerals [15]. The presence of bran in the whole wheat flour, which is obtained from the seed coat of the wheat particles, also increases the fiber content of the pasta. In light of its widespread consumption, diverse ingredients have been incorporated into the pasta dough to assess their compatibility and to evaluate their potential to enhance the nutritional profile, texture, flavor, and cooking qualities of the resultant product. It has also been proposed that sensory attributes, such as aroma, appearance, and shelf life, can be improved by the addition of additional ingredients. Recently, the use of various additives, such as fish powder [16]; food industry by-products, such as olive pomace [17]; fermented black chickpea flour [18]; brewing by-products, such as trub [19]; and many more have been explored to fortify pasta, with the primary objective of improving not only the nutritional profile but also the textural and cooking qualities.

Recent studies have increasingly explored the potential applications of oleogel beyond its conventional use as a bakery fat replacement, with promising outcomes observed in various food products. For instance, Oh et al. (2020) highlighted the efficacy of candelilla wax/soybean oil oleogel in reducing noodle firmness, enhancing dough viscosity, and enlarging noodle pore size, which ultimately leads to reduced cooking time [20]. Similarly, Vernon-Carter et al. (2020) investigated the impact of candelilla wax/canola oil oleogel on maize tortillas, observing a decrease in tortilla hardness alongside increased tensile strength [21]. These studies highlighted the fact that the inclusion of oleogel in non-bakery products influences its appearance and textural properties. Drawing inspiration from these findings, this study replaced a portion of water in the pasta composition with oleogel sourced from a previous study by Chaturvedi et al. (2023), wherein the effects of incorporating stearic acid (SAC) on the properties of candelilla wax/groundnut oil oleogel was explored [22]. Candelilla wax (CW) served as the gelator, facilitating gelation in the liquid phase, i.e., groundnut oil (GO). CW, an FDA-approved plant wax which is rich in odd-numbered n-alkanes and trace esters, yields stable oleogels with high oil binding capacity upon crystallization in vegetable oil. On the other hand, GO is characterized by its abundance of poly- and monounsaturated fatty acids and thus promotes heart health and cholesterol control. The optimal composition of the oleogel that contained SAC in the candelilla wax/groundnut oil oleogel at a concentration of 0.015% (w/w) was used [22]. Based upon this foundation, the current study extends the application scope of the optimal oleogel formulation to evaluate the cooking and textural properties of whole wheat flour pasta. The pasta formulations were characterized through various physicochemical analyses, including color analysis using a colorimeter, measurement of thickness and width using a digital screw gauge and vernier caliper, evaluation of surface topology using a stereo zoom microscope and FESEM, assessment of cooking qualities

through water absorption capacity and swelling index measurements, determination of moisture content, and analysis of mechanical and textural properties via stress relaxation and puncture tests. Finally, Fourier transform infrared (FTIR) spectroscopy was employed to explore the chemical interactions among the pasta constituents.

2. Materials and Methods

2.1. Materials

The commercially available GO (brand: Engine brand; make: Shree Hari Industries, Rajasthan, India) used for the oleogel preparations was acquired from a local grocery store in Rourkela, India. The CW employed in the study was obtained from the company Nature's Tattva, New Delhi, India. The SAC utilized in this study was purchased from Loba Chemie Pvt. Ltd. (Mumbai, India). Additionally, the commercially available whole wheat flour (Brand: Aashirvaad, ITC Limited, India) was procured from the local market (Rourkela, Odisha, India). The flour is made from the wheat variety of *Triticum aestivum* [23]. As per the packaging, the composition of the flour (per 100 g) is as follows: protein—10.5 g, carbohydrate—76.8 g, total fat—1.4 g, and sodium—2.3 mg.

2.2. Preparation of Oleogel Samples

A sample of oleogel containing 5% CW and 3 mg (or 0.015% w/w) of SAC in GO was prepared as per the method discussed in one of the previous studies [11]. In brief, a stock solution of SAC, with a concentration of 0.1%, was prepared in GO. The stock solution of SAC was then added to a mixture of 5% (w/w) CW and GO to achieve the desired final concentration of 3 mg (or 0.015% w/w) of SAC in the oleogel sample. Then, the mixture was subjected to heating at 90 °C for 25 min, followed by continuous homogenization at 300 rpm for an additional 15 min at the same temperature. The hot mixture was then placed in a thermal cabinet, maintained at 25 °C, for 3 h. This resulted in the formation of the oleogel.

2.3. Pasta Preparation

The pasta was prepared according to the procedure described by [24], with slight modifications. This study used an automatic pasta-making machine (model: 16009; make: KENT RO System Ltd., Noida, India) to blend all the ingredients and extrude them in the shape of tagliatelle (ribbon pasta). The ingredients for preparing the control sample included whole wheat flour and water. For the oleogel-incorporated pasta, four samples were prepared by replacing the water with the oleogel. The replacement of the water was at the levels of 2.5%, 5%, 10%, and 15% w/w. The compositions of all the pasta samples are tabulated in Table 1.

Table 1. Composition of pasta samples.

Samples	Wheat Flour (g)	Water (g)	Oleogel Amount (g)	Total Amount (g)
P0	250	95	0	345
P2.5	250	92.625	2.375	345
P5	250	90.25	4.75	345
P10	250	85.5	9.5	345
P15	250	80.75	14.25	345

Firstly, the oleogel and water were heated at 90 °C for 25 min in a water bath and then weighed in appropriate proportions in a beaker (100 mL). The pasta dough was prepared by adding wheat flour to the pasta maker and then adding the oleogel/water mixture while the machine continuously stirred the wheat flour. When the dough was properly kneaded, it was extruded through a shaping die. The extruded pasta (~150 g) was collected into air-tight containers in three parts. One portion, weighing around 50 g, was reserved for the analysis of uncooked pasta and allowed to rest for 10 min to ensure uniform hydration. The remaining two portions, totaling approximately 100 g, were set aside for cooking after

an hour. These portions were added to boiling water (1.5 L) in a steel container with a 5 L capacity. After 12 min of cooking, approximately 50 g of pasta was sampled for analysis, with the remainder sampled after 15 min. Prior to each analysis, the samples were air-dried for 5 min to remove excess moisture.

2.4. Thickness and Width of the Pasta

The dimensions (thickness and width) of both the uncooked and cooked pasta strands were determined using a digital screw gauge (Model: EM025; Make: Digital Micrometre, Yuzuki, China) and a vernier caliper (Model: IP54 Metal case Digital caliper; Make: Advance, West Bengal, India), respectively, in accordance with prior studies by Kadiri et al. in 2020 [25].

2.5. Colorimetry

The color profiles of the pasta were investigated using a colorimeter. A colorimeter instrument built in-house was used to test the pasta samples [26]. For this, freshly extruded and cooked pasta strands were used. Initially, black and white placards were used to calibrate the instrument. After taking pictures of the pasta samples using the device's camera, the L*, a*, and b* values of the device's color parameters were measured. With the help of color parameters, we were able to calculate the whiteness index (WI), yellowness index (YI), and absolute color differences (ΔE) [27]. The color indexes were calculated using the formula written below:

$$WI = 100 - \sqrt{(100 - L^*)^2 + (a^*)^2 + (b^*)^2} \quad (1)$$

$$YI = 142.86 \frac{b^*}{L^*} \quad (2)$$

$$\Delta E = \sqrt{(L_c^* - L_z^*)^2 + (a_c^* - a_z^*)^2 + (b_c^* - b_z^*)^2} \quad (3)$$

where L_c^*, a_c^*, and b_c^* denote the parameter values of the control pasta sample, and those with subscript 'z' are the pasta samples containing oleogel.

2.6. Microscopy

2.6.1. Surface Topology

To obtain an insight into the surface topography of the pasta samples (both uncooked and cooked), the pasta strands were examined under a stereo zoom microscope (model: SM-2TZ; make: AMscope, Irvine, CA, USA).

2.6.2. FESEM

The microstructural analysis of the pasta sample surfaces was conducted using a field emission scanning electron microscope (model: FEI Novanano SEM 450; make: Thermo Fisher Scientific, MA, USA). For the analysis, the samples were freeze-dried for 48 h, and sputter-coated with gold before the analysis.

2.7. Cooking Qualities of Pasta

Water Absorption Capacity (WAC) and Swelling Index (SI)

The water absorption capacity and swelling index were measured to quantify the cooking qualities of the pasta. To determine the percentage of water absorbed by the pasta samples, i.e., the water absorption capacity of the pasta samples, after cooking for a duration of 12 and 15 min, the WAC was evaluated according to the method proposed by the Association of Official Agricultural Chemists (AOAC) [28]. For this, the uncooked pasta strands were cut and weighed on a weighing balance. These strands were subsequently

cooked and re-weighed. The formula in Equation (4) was used to calculate the water absorption capacity, as follows:

$$\text{WAC} = \frac{\text{Final weight} - \text{Initial weight}}{\text{Initial weight}} \times 100 \quad (4)$$

The method for determining the swelling index of pasta was adopted by Tudorica et al. (2002) [29]. The weight of the pasta strands was recorded after cooking for 12 and 15 min. These strands were then kept for drying at 105 °C till their weight became constant. The SI was determined using Equation (5). Additionally, the dry matter was also calculated using Equation (6).

$$\text{SI} = \frac{\text{Weight of cooked pasta} - \text{Weight of pasta after drying}}{\text{Weight of pasta after drying}} \quad (5)$$

$$\%\ \text{Dry matter} = \frac{\text{Final weight of cooked pasta after drying}}{\text{Initial cooked weight of pasta}} \times 100 \quad (6)$$

2.8. Moisture Analysis

To determine the amount of water contained in the pasta samples, a moisture content analysis was performed using a moisture analyzer machine (model: PGB1MB; Wensar Weighing Scales Limited, Maharashtra, India). For this, the pasta samples (cooked and uncooked) were cut into tiny pieces and measured to weigh around 2 g on an aluminum foil-wrapped platform-cum-weighing balance integrated within the machine. Then, the samples were maintained at a temperature of 180 °C until the machine signaled a constant moisture content value (in %) through an audible beep. After that, the final reading was noted down. The machine computed the % moisture content in the samples using the following equation:

$$\%\ \text{Moisture content} = \frac{M_f - M_i}{M_i} \quad (7)$$

where M_f denotes the weight of the pasta samples post-heating, and M_i represents the weight of the pasta samples pre-heating.

2.9. Texture Analysis

The stress relaxation and puncture tests were used to infer the mechanical properties of the pasta samples.

2.9.1. Stress Relaxation

The stress relaxation (SR) experiment was carried out using the texture analyzer (model: HD plus, make: Stable Micro Systems, Surrey, UK), which was fitted with a load cell of 5 kgf. For the analysis, a single strand of uncooked pasta sample was stabilized in the film support rig. Then, a spherical probe (diameter: 5 mm) was used to provide a strain of 1 mm after a trigger force of 5 g at a constant speed of 1 mm/s. The strain was applied for 60 sec. During the applied strain duration, the alterations in the force values were recorded. The above process was also repeated for the cooked pasta. Before the analysis, the surface water on the pasta (if present) was blotted using filter paper.

Subsequently, %SR was quantified for each oleogel sample using Equation (8), as follows [22]:

$$\%\text{SR} = \frac{F_0 - F_R}{F_0} \times 100 \quad (8)$$

where F_0 is the maximum force in the SR curve, and F_R is the residual force in the SR curve.

2.9.2. Puncture Test

The puncture test was also conducted using the texture analyzer. For the study, a single strand of a pasta sample was immobilized in a film support rig. Then, a spherical

probe (Diameter: 5 mm) was allowed to travel a distance of 10 mm after a trigger force of 5 g.

2.10. FTIR

The chemical interactions of the constituents present in the prepared pasta samples were analyzed through FTIR spectroscopy. An FTIR spectrophotometer (Model: Alpha-E; Make: Bruker, Bremen, Germany) equipped with an attenuated total reflectance (ATR) that was equipped with a zinc selenide (ZnSe) crystal was employed to acquire the IR absorption spectra of both the raw materials and the prepared pasta samples. The scanning of the raw materials and samples was conducted in ATR mode, covering a wavenumber range of 4000–500 cm^{-1}, each with 30 scans at a spectral resolution of 4 cm^{-1}. The experiment involved conducting the spectral analysis in triplicate.

2.11. Statistical Analysis

Data were collected in at least triplicate in all the above analyses and presented as mean ± standard deviation. Furthermore, for the confirmation of the significant differences ($p < 0.05$) among the samples, a student *t*-test was performed.

3. Results

3.1. Visual Appearance of Pasta Samples

In addition to its nutritional qualities, the visual appearance of food is an important factor influencing consumer preferences. The visual appearance and quality of food are also intricately connected. Several noteworthy observations were made upon visual inspection of the pasta samples depicted in Figure 1. Firstly, the control sample (P0) exhibited zig-zag edges with a rough outer surface and a yellowish-brown color. Conversely, upon the addition of oleogel, the uncooked sample progressively acquired smoother edges and texture. Furthermore, the extruded pasta samples exhibited a curvature towards one side, which was attributable to a reduced length on one side. This resulted in their distinctive C-shape, which intensified at higher levels of water replacement with oleogel, which is also evident from Figure 1. In the uncooked pasta samples, the replacement of the water counterpart of pasta dough with an equivalent amount of oleogel resulted in drier, stiffer, and more compact pasta strands, which was visually translated into slightly reduced thickness, as illustrated in Figure 1. Additionally, the incorporation of oleogel was related to the gradual darkening in the color of the pasta samples compared to P0. These changes are depicted in Figure 1. Upon cooking the pasta samples, a notable color change was observed, giving them an appearance that was distinct from that of the uncooked state. The cooking process led to the melting of the oleogel trapped within the pasta strands, and it was subsequently released into the surrounding water. This also caused the formation of pores within the samples [20]. As the extent of the oleogel release varied, it resulted in the exhibition of different colors by the cooked samples.

3.2. Thickness and Width of Pasta Samples

The measurement of the dimensions (thickness, diameter, width, etc.) of foods such as pasta and noodles serves a purpose in food analysis and quality control. The dimensions also impact the cooking time and texture of these foods. Figure 2a presents the thicknesses of the pasta samples. Compared to the other uncooked pasta samples, P10 showed a significant decrease in its thickness compared to P0 ($p < 0.05$). The thickness of P2.5 was similar to that of P5, P10, and P15 ($p > 0.05$). Furthermore, P5 showed a significantly higher thickness than P10 ($p < 0.05$) but was similar to P15 ($p > 0.05$). Also, P10 showed a significantly lower thickness than P15 ($p < 0.05$). After 12 min of cooking, all the samples, except P10, showed an increase in thicknesses compared to P0 ($p < 0.05$). All the oleogel-containing pasta samples showed similar thicknesses ($p > 0.05$). On the other hand, after 15 min of cooking, all the pasta samples that contained oleogel showed a significant increase

in their thicknesses compared to P0 ($p < 0.05$). However, there were no variations among the thicknesses of the 15 min cooked oleogel-containing pasta samples ($p > 0.05$).

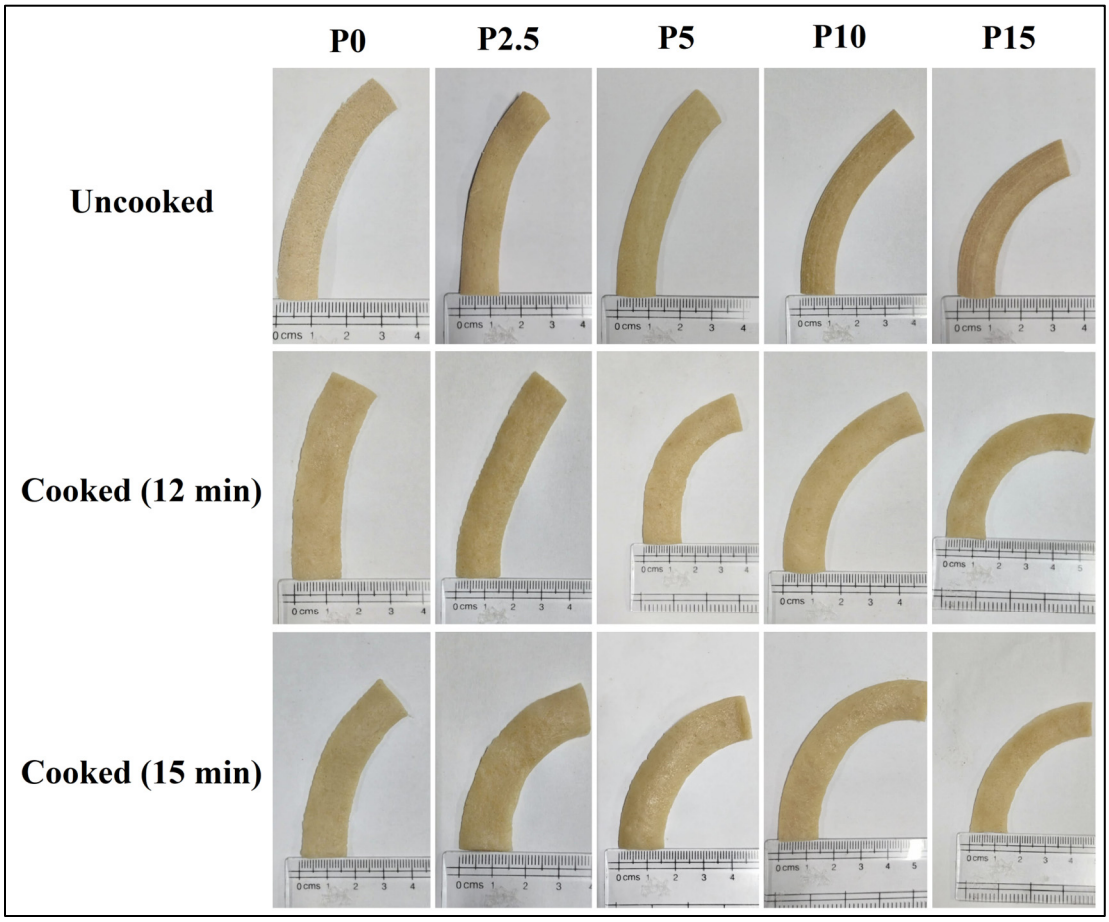

Figure 1. Photographs depicting various samples of pasta.

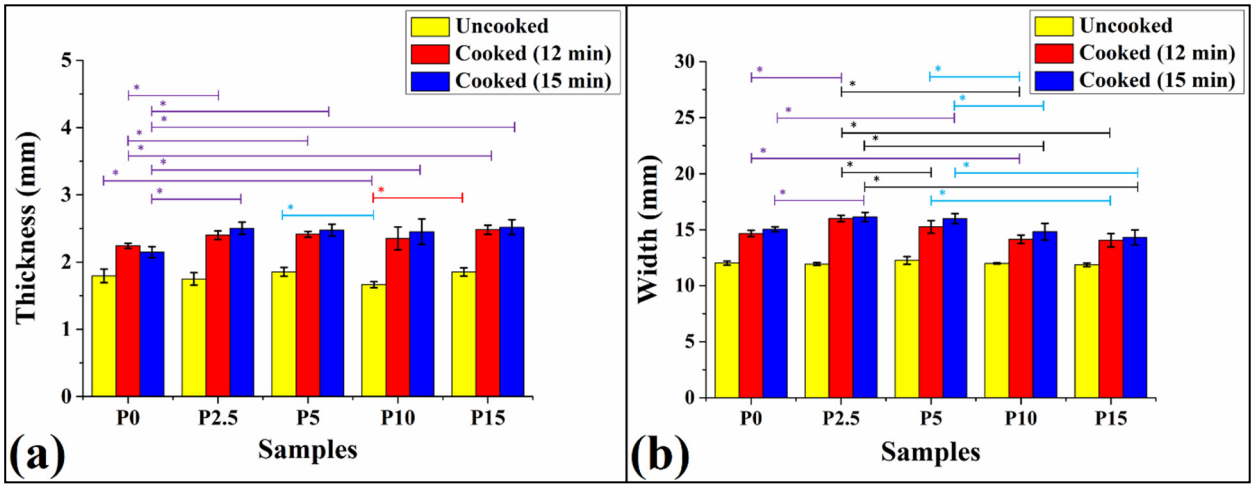

Figure 2. Physical measurements of the pasta samples: (**a**) thickness and (**b**) width. The symbol '*' on the bars shows the significant difference between the two samples.

In a similar manner to the thickness, the width of the pasta samples was also measured (Figure 2b). The analysis of the widths of the pasta samples can also be approximated through reference to Figure 1. There was no variation in the width of the uncooked pasta samples even after the addition of oleogel ($p > 0.05$). After 12 min of cooking, P2.5 showed

a significant increase, while P10 showed a significant decrease in width values compared to P0 ($p < 0.05$). Among the oleogel-containing pasta samples, P2.5 showed a significantly higher width value than P5, P10, and P15 ($p < 0.05$). Furthermore, P5 showed a significantly higher width value than P10 and P15 ($p < 0.05$), while P10 showed a comparable width value to P15 ($p > 0.05$). After 15 min of cooking, P2.5 and P5 showed a significant increase in their width values, compared to P0 ($p < 0.05$), whereas P10 and P15 showed similar width values to that of P0 ($p > 0.05$). On the other hand, among the oleogel-containing pasta samples, P2.5 and P5 showed a significantly higher width value than P10 and P15 ($p < 0.05$). The width values of P10 and P15 were similar ($p > 0.05$).

3.3. Colorimetry

Food color is a crucial sensory attribute that influences consumer perceptions, expectations, and overall experience of a product. The analysis of the change in color upon the addition of oleogel in the pasta samples, before and after cooking, was performed by colorimetric analysis. The CIELAB model was used to measure the color parameters, i.e., L*, a*, and b*, which referred to the lightness, redness/greenness (+/−), and yellowness/blueness (+/−) of the samples, respectively [10]. As shown in Figure 3a, the L* values of all the uncooked pasta samples were within the range of 79–85. Incorporating oleogel within the samples did not significantly affect the L* values in comparison to P0 ($p > 0.05$). Among the oleogel-containing pasta samples, P15 showed a significantly lower L* value compared to P2.5 and P5 ($p < 0.05$). The a* value of the uncooked pasta, as displayed in Figure 3b, was within the range of 4–14, indicating the presence of a reddish hue in the samples. In general, the color values of oleogels are mostly determined by the raw materials utilized to make them [30]. The whole wheat flour utilized in this study contained bran particles, which possess a dark reddish-brown color, and their inclusion can influence the end product [31], which potentially explains the reddish hue observed in all the pasta samples. Additionally, the oleogel used in the study may have contributed to the increased redness of the samples when combined with the pasta. This might be due to the formation of a starch–lipid complex (specifically, an amylose–lipid complex) after adding oleogel to the pasta samples [32].

All the oleogel-containing pasta samples exhibited a significant increase in their a* values ($p < 0.05$) in comparison to P0. This suggested a rise in the reddish hue with the incorporation of the oleogel in the pasta samples. Among the oleogel-incorporated pasta samples, P2.5 showed a similar a* value to P5, whereas P5 showed a similar a* value to P10 ($p > 0.05$). The a* value of P15 was significantly higher than that of the rest of the pasta samples ($p < 0.05$). As with the a* values, all the uncooked pasta samples demonstrated a significant increase in their b* values ($p < 0.05$) (ranging from 41 to 77) with respect to P0 upon oleogel incorporation (Figure 3c). This indicated an increase in the yellowish tint in the samples in which the oleogel was incorporated. The yellowish tint could be attributable to the carotenoid pigment present in the GO in the oleogel [33,34]. P2.5 showed comparable b* value to that of P5 and P15 ($p > 0.05$).

Figure 3d illustrates the whiteness index (WI) values, derived from the L*, a*, and b* values, of the samples. It was observed that the WI of P0 was the highest among all the pasta samples ($p < 0.05$). At lower amounts of oleogel in P2.5 and P5, there was a significant reduction in the WI values compared to P0 ($p < 0.05$). The decrease in WI could be due to the increase in the concentration of the starch–lipid complex [32]. An additional increase in the oleogel content in P10 resulted in an increase in the WI value, which was significantly greater than that of the other oleogel-incorporated samples ($p < 0.05$). In P15, where the oleogel content was the highest, there was a marked reduction in the WI value compared to P0, P5, and P10 ($p < 0.05$). The yellowness index (YI) values of the uncooked pasta samples are presented in Figure 3e. It can be observed that the YI of P0 was the lowest. The incorporation of oleogel in P2.5 significantly increased its YI value compared to P0. A subsequent increase in the oleogel content in P5 did not significantly affect the YI value compared to P2.5 ($p > 0.05$). A further increase in the oleogel content in P10 significantly

reduced its YI to a minimal value among all the oleogel-containing pasta samples. When the oleogel content was the highest (in P15), there was a consequent increase in the YI value, which was similar to that of P2.5 ($p > 0.05$). Figure 3f presents the absolute color difference (ΔE) between the samples with respect to the P0. The ΔE value helps to determine whether the human eye could detect the color variation among the samples. A ΔE value greater than 5 is generally considered to be a noticeable color variation [35,36]. The values of ΔE for the uncooked pasta samples were found to be greater than 5. This indicates that the color difference due to the addition of oleogel caused a perceivable color change in the pasta samples. The color change in the pasta samples can also be assessed by referring to Figure 1. The increase in the oleogel content caused the lowering of the ΔE value, which reached a minimum in P10. An additional increase in the oleogel concentration increased the ΔE value.

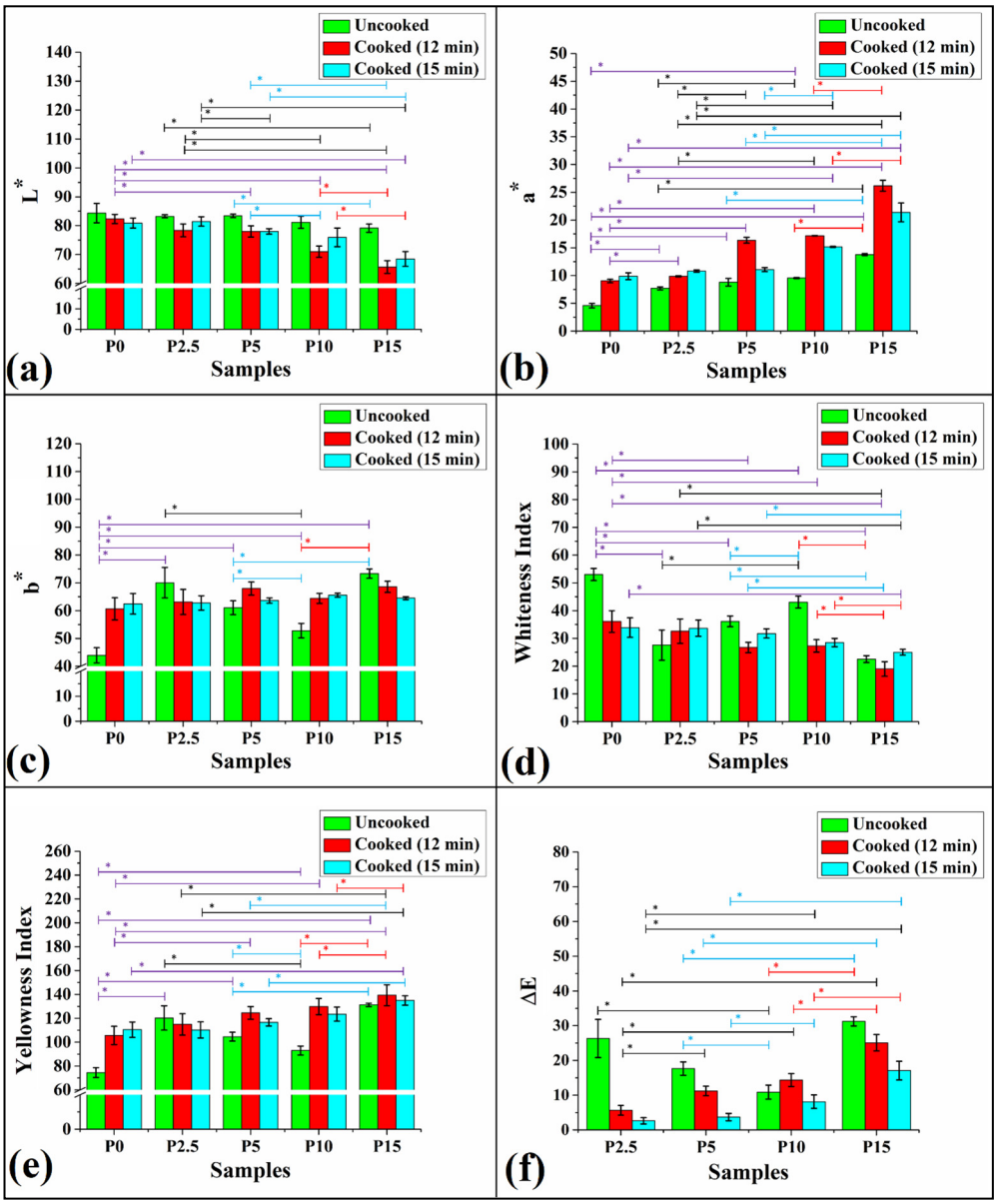

Figure 3. Color parameters of the pasta samples: (**a**) L*, (**b**) a*, (**c**) b*, (**d**) WI, (**e**) YI, and (**f**) ΔE. (The symbol '*' on the bars shows the significant difference between the two samples at $p < 0.05$).

Overall, the L* values were lower in the cooked pasta samples than in the uncooked pasta samples (Figure 3a). As the oleogel concentration was increased, the reduction in the L* values was evidently increased. The a* values of the cooked samples were increased

compared to those of the uncooked pasta samples. This suggested that there was an increase in the reddish hue of the pasta samples after cooking. Interestingly, no specific trend in the b* values could be observed among the uncooked and the cooked pasta samples. In general, the WI values of the cooked pasta samples were lower in comparison to those of the uncooked pasta samples, except for P2.5 and P15. The WI values of the uncooked and cooked P2.5 and P15 appeared to be similar ($p > 0.05$). Furthermore, the YI values of P0, P5, and P10 were markedly increased after cooking ($p < 0.05$), whereas the YI values of P2.5 and P15 did not show a marked change after cooking ($p > 0.05$).

3.4. Microscopy

3.4.1. Surface Topology

Figure 4 displays the surface topographies of both the uncooked and the cooked pasta samples. The control (P0) sample exhibited cracks and grooves (marked by red and yellow arrows, respectively) on the surface [37], which decreased in P2.5 and P5 as the oleogel was incorporated into the pasta samples. Oleogels have also been observed to contribute to the smoothness of dough [38,39]. Surprisingly, in P10 and P15, the surface topography of the samples showed the existence of darker spots (marked by black arrows), which again might be related to the starch–lipid complex formation, as was evident in the colorimetric analysis [32,40]. Darker spots might also be caused by the coating of the flour particles with the oleogel [41]. The P15 sample showed a higher number of darker spots. Scientific studies have indicated that starch–lipid complex formation can decrease the starch swelling power and solubility, thus delaying its gelatinization [32].

After cooking, the starch underwent gelatinization. As a result of gelatinization, all the pasta samples showed a smooth topography, which appeared slightly darker than the uncooked pasta (Figure 4). The existence of absorbed water molecules close to the surface of the pasta can explain the bright spots (marked by green arrows) seen in the cooked pasta samples. It might be possible that these water molecules are present within the pores or grooves formed during the cooking process. Overall, all the 12 min cooked pasta samples apparently showed similar surface smoothness. The pasta samples that were cooked for 15 min showed the existence of bulged (or swelled) surfaces (marked by violet arrows) compared to the 12 min cooked pasta. Such an observation may be attributable to the increased absorption of water after 15 min compared to the 12 min cooking process. The microscopic observations can also be well correlated with the morphology of the pasta samples, as presented in Figure 1.

3.4.2. FESEM

FESEM was employed to examine the surface and microstructural characteristics of both the uncooked and the cooked pasta samples (Figures 5 and 6). The surface of P0 exhibited grooves and irregularities. When oleogel was added to the pasta, it dramatically changed its texture. The micrographs of the uncooked oleogel-containing samples suggested that the pasta matrices were composed of globular particles. In P2.5, P5, and P10, the globular particles were tightly packed. However, in P15, defects (marked by the yellow arrows) were observed on the surface. This suggested that when the water was replaced with oleogel in higher amounts, there was a compromise in the structural integrity of the pasta matrices. After cooking the pasta samples, the starch granules underwent gelatinization, leading to surface morphology changes, as reported in some studies [42,43]. During cooking, the oleogel in the pasta samples leached out of the samples, thereby creating pores. The melting of oleogel during hot-air drying and cooking has been documented by Oh et al. (2020), who found that it led to the creation of void regions. These voids might facilitate heat transfer during cooking and, thus, enhance rehydration [20]. Overall, an increase in the oleogel content increased the porous structures (marked by the pink arrows) on the surface. Furthermore, an increase in the cooking time from 12 min to 15 min caused a rise in the number of porous structures on the pasta matrix surface.

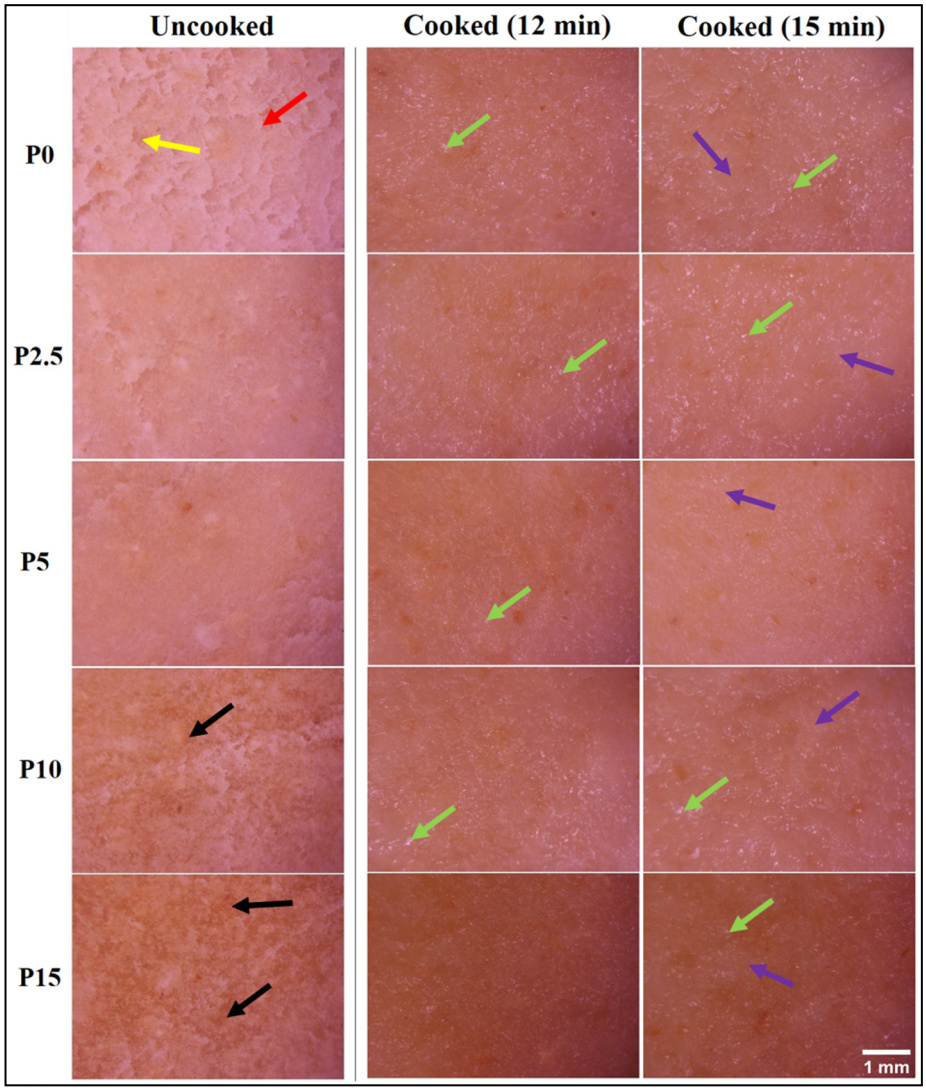

Figure 4. Surface topography of the uncooked and cooked (for 12 min and 15 min) pasta samples. (Red and yellow arrows indicate cracks and grooves; black arrows indicate the darker spots; green arrows indicate the bright spot; and violet arrows indicate bulged surfaces).

The FESEM micrographs of the uncooked pasta samples at higher magnification are provided in Figure 6 (magnification: 1000× *g*). The micrographs showed that the starch granules (indicated by the red arrows) were embedded within the gluten protein matrices (represented by the blue arrows), as also indicated in an investigation by Singh et al. 2021 [44]. The starch granules were larger than the gluten proteins, which appeared as smaller-sized globular particles, as similarly reported by Singh et al. 2021 [44]. As the composition of the pasta samples was changed, there was a change in the size and shape of the starch granules and gluten matrices. In P0, the starch granules appeared predominantly oval or circular, as also reported in various studies [44–46]. However, with increasing amounts of oleogel (by replacing the equivalent amount of water), the starch granules lost their oval shape, and in the P15 sample, they exhibited distorted and shrunken appearances, possibly due to their lower water concentration. Furthermore, the starch granules may have been coated by oleogel, preventing them from absorbing water [47] during the formation of pasta dough. This can well explain the changes in the surface texture of the pasta samples, as observed in stereo zoom microscopy (Figure 4) and low-magnification FESEM images (Figure 5).

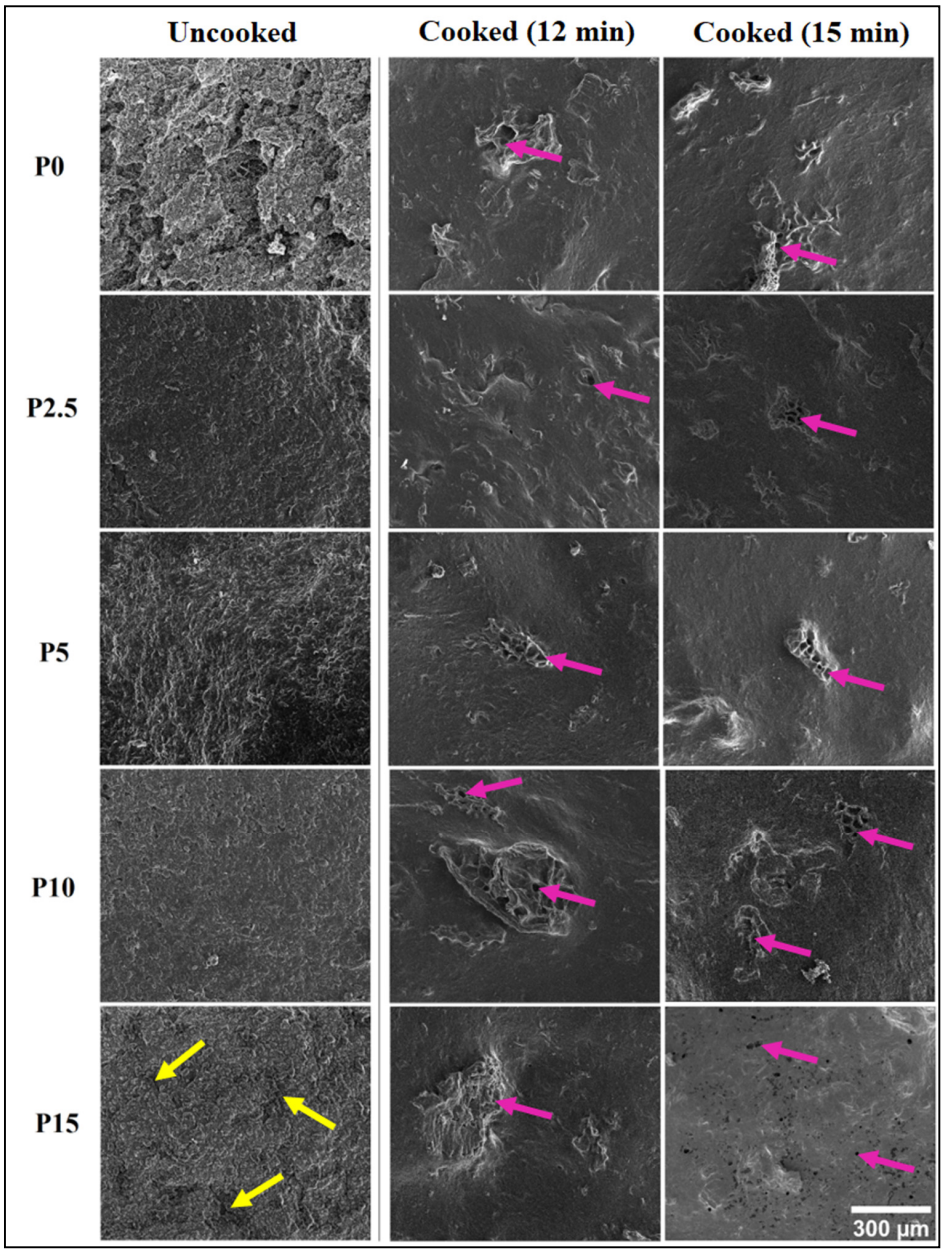

Figure 5. FESEM micrographs of all the pasta samples (yellow arrows indicate defects on the surface of the pasta, whereas pink arrows indicate pores). (Magnification: 250×).

3.5. Cooking Qualities of Pasta

Water Absorption Capacity (WAC), Swelling Index (SI), and Dry Matter

WAC refers to the capability of food material to absorb and retain water. Figure 7a depicts the WAC of cooked pasta samples. In general, there was a reduction in the WAC as the oleogel content increased. The WACs of P0 and P2.5 had similar values ($p > 0.05$) after cooking for 12 min and 15 min. However, a further rise in the oleogel concentration considerably decreased the WAC ($p < 0.05$) compared to P0. Like the WAC, the SI of the pasta samples after cooking for 12 and 15 min also showed a decreasing trend (Figure 7b). SI pertains to the capacity of a food product, specifically one containing starches, to expand upon exposure to water. Overall, the incorporation of oleogel prevented the pasta samples from swelling after cooking. Both of the above results might be attributable to the hydrophobic character provided by the oleogel to the pasta samples, which restricted the ability of the pasta samples to absorb and, consequently, to swell. These observations have also been concluded by Oh et al. 2020 [20] and González et al. 2021 [48] in similar

studies with noodles and pasta, respectively. The hydrophobic character is due to the complex formation between oleogel and amylose [48]. It has been reported that starch–lipid complexes form an insoluble layer on the surface of starch granules, thereby delaying water absorption and, hence, increasing gelatinization temperature [32].

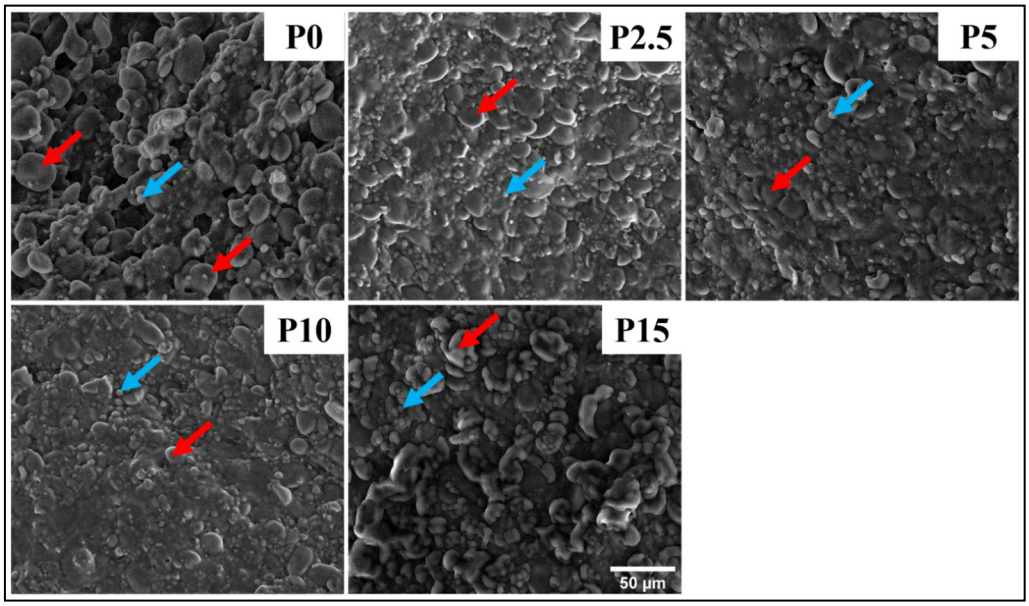

Figure 6. FESEM images of uncooked pasta samples at higher magnification show the starch granules and gluten protein (red arrows indicate starch granules, whereas blue arrows indicate gluten protein granules). (Magnification: 1000×).

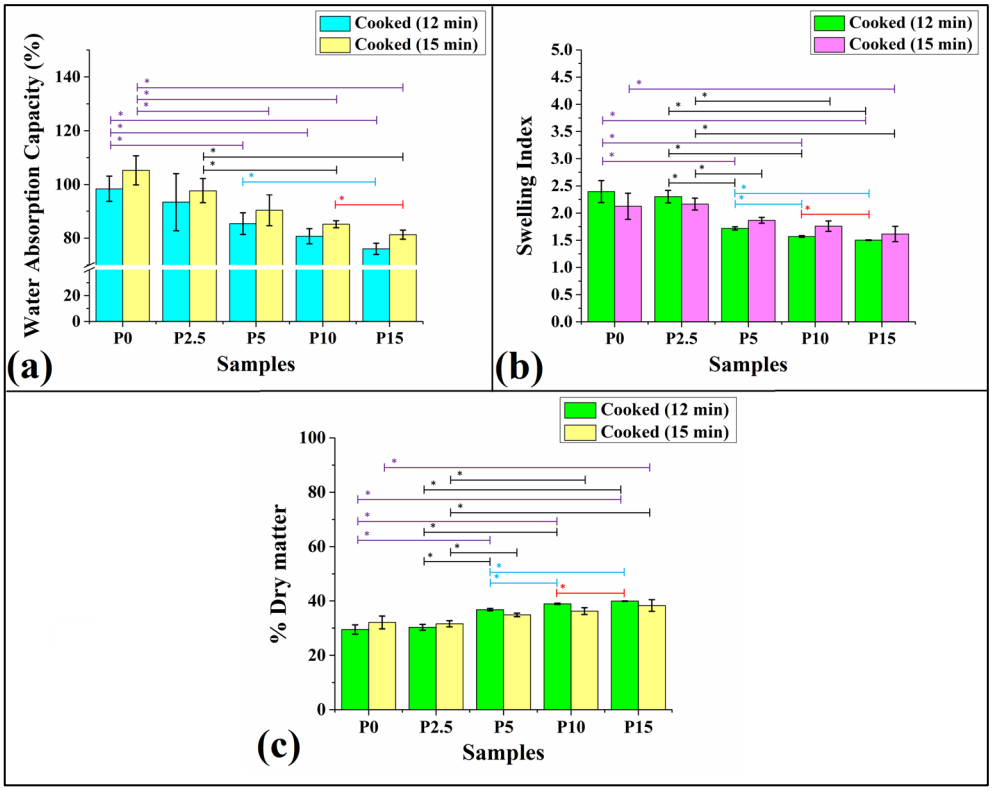

Figure 7. Cooking quality of pasta: (**a**) water absorption capacity (%); (**b**) swelling index; and (**c**) % dry matter content of the pasta samples. (The symbol '*' on the bars shows the significant difference between the two samples at $p < 0.05$).

In contrast to water absorption capacity (WAC) and swelling index (SI), the percentage of dry matter in the pasta samples exhibited an increasing trend after cooking (Figure 7c). Specifically, P5, P10, and P15 demonstrated a significant increase in dry matter compared to P0 after 12 min of cooking ($p < 0.05$). Among all the oleogel-laden samples, P15 exhibited the highest percentage of dry matter content ($p < 0.05$). Similarly, after 15 min of cooking, P15 demonstrated a significant increase in dry matter compared to P0. Additionally, among all the oleogel-containing samples, the P5, P10, and P15 samples demonstrated a significant increase in dry matter compared to P2.5. This increment of dry matter after cooking in the oleogel-containing pasta can be correlated with low cooking loss and improved quality; this is consistent with findings from a previous study where the addition of oleogels in noodles significantly lowered cooking loss and improved quality [20]. Overall, it can be concluded that the addition of oleogel to the pasta samples increases their quality with a consequent decrease in cooking loss.

3.6. Moisture Analysis

Figure 8 displays the recorded moisture content of both the uncooked and the cooked pasta samples. The moisture content of the uncooked pasta samples was observed to be ~30% (w/w). The moisture content of P0 and P2.5 had a similar value ($p > 0.05$). However, there was a marked reduction in the moisture content of the other oleogel-containing samples compared to P0 ($p < 0.05$). The highest moisture content in P0 was due to the highest water content in the P0 dough. Similar results were also reported by Witek et al. (2020), where an amount of water was replaced with different egg-derived materials, which resulted in decreased moisture content in the enriched pasta compared to the control [49]. The cooked samples showed higher moisture content than the uncooked samples due to the absorption of the water molecules. Pasta with a high moisture content (i.e., a high cooking weight) may be chewy. As the cooking time was increased from 12 min to 15 min, there was a slight increase in the moisture content. This observation can be related to the WAC, where it was found that the WAC improved as cooking time increased.

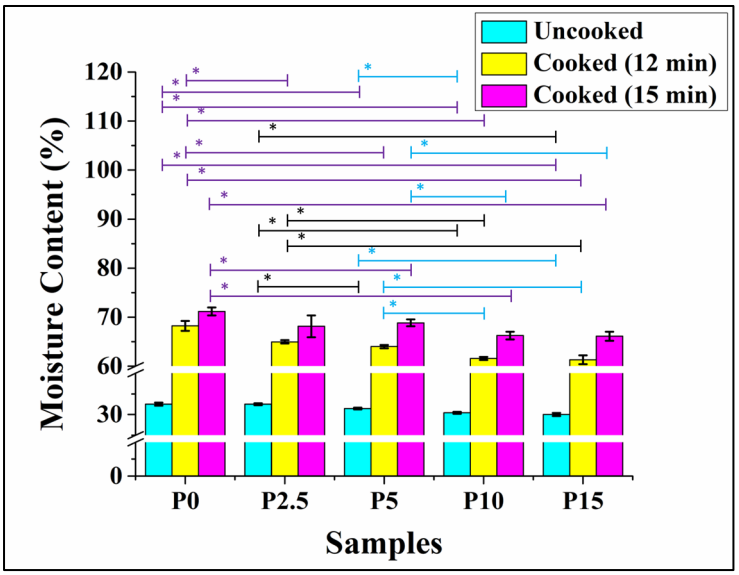

Figure 8. Moisture content (% m) of the pasta samples. (The symbol '*' on the bars shows the significant difference between the two samples at $p < 0.05$).

3.7. Texture Analysis

3.7.1. Stress Relaxation Test

The stress relaxation analysis was carried out to investigate the behavior of the pasta samples under mechanical stress over a period of time. For this purpose, the pasta was subjected to deformation, and then, the decrease in stress was recorded over time. Stress relaxation data have been employed to analyze the viscoelastic behavior of food materials, which divulges information about the textural aspects of food materials, such as staling and the quality of the food products [25]. Among the components of pasta, the major influence on texture is primarily attributable to the wheat component. The proteins present in wheat, particularly gluten, play a crucial role in the determination of the pasta's texture. Gluten proteins help to create a cohesive, viscoelastic dough when water and wheat flour are combined. This also significantly impacts the firmness, chewiness, and overall texture of cooked pasta [44,50].

Figure 9a–c represent the stress relaxation curves of uncooked [49], 12 min cooked, and 15 min cooked pasta samples [51]. The parameters (F_0, F_{60}, and %SR) determined from the stress relaxation profiles are presented in Figure 9d–f. As the oleogel concentration was increased, the F_0 values of the pasta samples also correspondingly improved. The F_0 values of the pasta samples decreased when the cooking time was extended (from 12 to 15 min) ($p < 0.05$). The hardness of pasta is an essential characteristic because pasta with a high hardness value has a firm character [52]. Increased firmness contributes to a desirable mouthfeel and texture and is also associated with reduced stickiness, which is generally preferred or gustatorily accepted [44]. Interestingly, the F_{60} values (which are markers of the inherent stability of the polymer matrices) of the cooked pasta samples were higher than those of the uncooked pasta samples. The results suggest that the inherent polymer network stability of the cooked pasta was superior to that of the uncooked samples. Among both the 12 min and 15 min cooked pasta samples, a significant increase in inherent polymer network stability (F_{60}) was observed with an increase in the oleogel content, compared to P0 ($p < 0.05$). The pasta samples (P0, P5, and P15) cooked for 12 min showed better polymer network stability than the same samples cooked for 15 min ($p < 0.05$). The above results could be correlated with FESEM micrographs (Figure 6), where a compact network was observed following the addition of oleogel. This network stability might have contributed to the reduced WAC and SI of the oleogel-containing samples by hindering the water diffusion into the starch granules. The lower SI due to the high protein network stability formed by gluten has been reported by Espinosa-Solis et al. 2019 [43]. Consequently, pasta with good polymer network stability could be associated with advantages such as improved texture retention, cooking tolerance, extended shelf life, reduced cooking loss, and consistent quality [53].

The %SR of the uncooked samples was greater than 70% and was far superior to that of the cooked samples (Figure 9f). This is suggestive of the predominant viscous component in the uncooked samples. On the other hand, the %SR of the cooked samples was lower than 50%, which indicates the cooked samples' dominant elastic behavior. The %SR of P10 was the highest and was significantly greater than that of P0 and P2.5 ($p < 0.05$). The elasticity of pasta is an essential property because it contributes to the strength of the pasta strands [52]. This was also evident from the F_{60} values. Interestingly, though the F_0 and F_{60} values of P10 were quite high, its %SR value was also considerably higher. This observation can be related to the reinforcing outcome exercised by the starch–lipid complex present in P10, as also observed in the surface topography. The presence of starch–lipid complexes might have weakened the long-term mechanical stability of the P10 polymer matrix, thereby resulting in a higher %SR value.

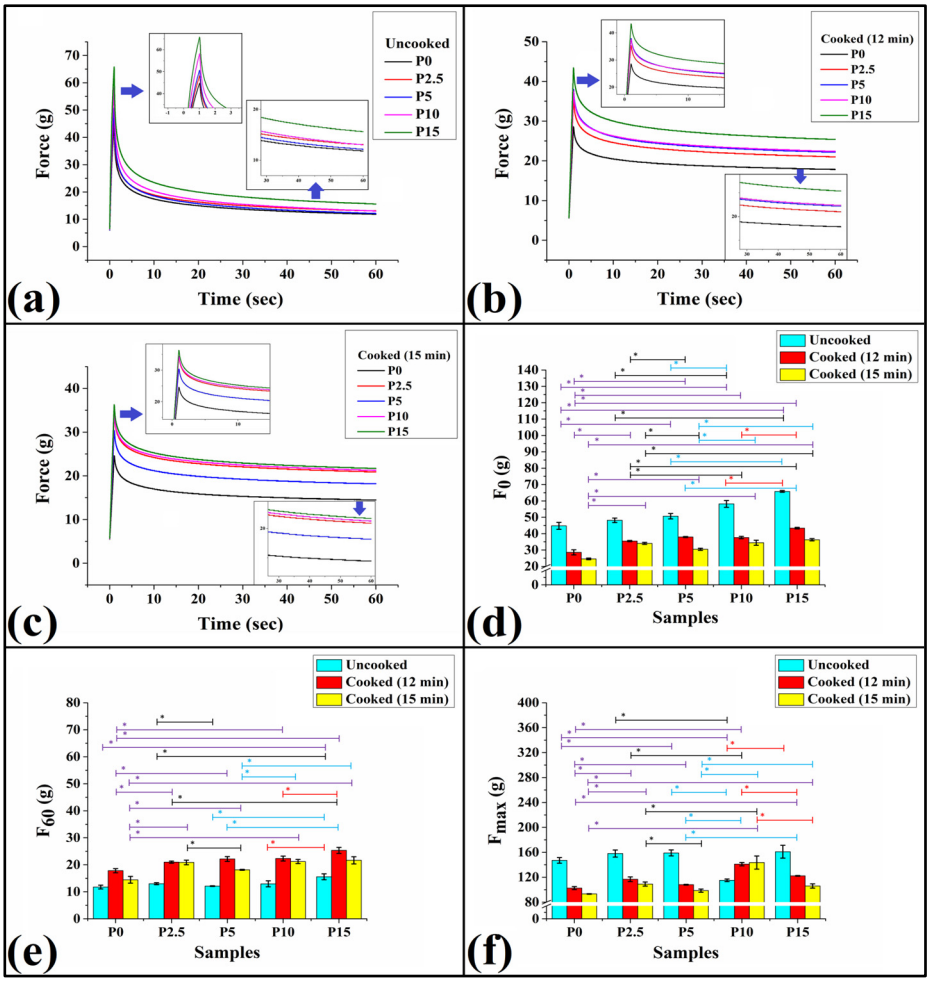

Figure 9. Stress relaxation profiles of (**a**) uncooked, (**b**) 12 min cooked, and (**c**) 15 min cooked pasta samples; test analysis parameters: (**d**) F_0, (**e**) F_{60}, and (**f**) % SR. (The symbol '*' on the bars shows the significant difference between the two samples at $p < 0.05$).

3.7.2. Puncture Test

A puncture test is a method that measures the force needed to penetrate a food sample using a probe or needle. It determines the mechanical strength and firmness of a food material [54] by evaluating its resistance to penetration [55]. During this test, a controlled force is applied to the food sample using a probe to induce penetration. This test helps to determine textural attributes, such as the hardness, brittleness, tenderness, and work of penetration [55].

The puncture test profiles of uncooked and cooked samples are represented in Figure 10a–c, and the results are compiled in Figure 10d,e. Among all the uncooked pasta samples, P10 had the lowest F_{max} value. This observation is in concordance with the %SR study, where it was found that the network stability of P10 was the lowest. Post-cooking, the F_{max} value of P10 increased, whereas it was interesting to note that there was a reduction in the F_{max} value in all the other samples. Among the uncooked pasta samples, the work of penetration (given by the area beneath the positive peak) of P0 had a similar value to that of the other pasta samples ($p > 0.05$). Notably, among the oleogel-containing samples, P10 showed the lowest work of penetration. Post-cooking, there was a reduction in the work of penetration in all the samples except P10. In P10, there was not much difference in the work of penetration of the uncooked pasta samples and the cooked ones. The "work of penetration" of the P10 samples after cooking was the highest among all the post-cooked pasta samples. This can be associated with the existence of

starch–lipid complexes in optimal quantities that might have acted as a reinforcing agent in the post-cooked P10 samples.

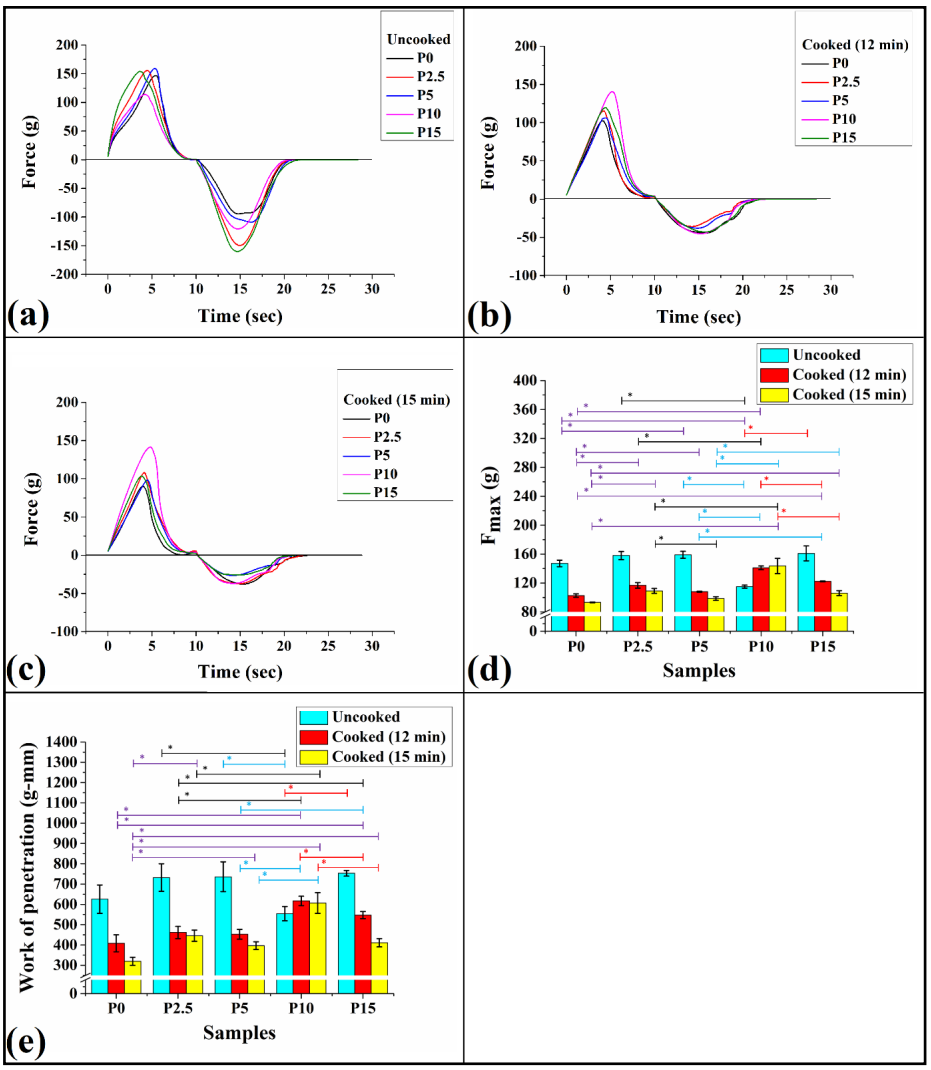

Figure 10. Puncture test profile of (**a**) uncooked, (**b**) 12 min cooked, and (**c**) 15 min cooked pasta samples; test analysis parameters: (**d**) F_{max} and (**e**) work of penetration. (The symbol '*' on the bars shows the significant difference between the two samples at $p < 0.05$).

3.8. FTIR

Figure 11 illustrates the FTIR spectra of the uncooked pasta and cooked pasta samples. The pasta samples containing oleogel exhibited peaks at similar wavenumbers. However, the peak intensity varied with the change in the composition. This was true for both the uncooked and cooked pasta samples. Analysis of the FTIR spectrum of the uncooked control pasta sample showed the presence of peaks at 3281 cm^{-1}, 2977 cm^{-1}, 2926 cm^{-1}, 1746 cm^{-1}, 1646 cm^{-1}, 1542 cm^{-1}, 1148 cm^{-1}, and 1016 cm^{-1}. A broad peak obtained at 3281 cm^{-1} indicated the presence of the -OH group in the control pasta sample. The interaction of water molecules with the pasta's constituent parts frequently results in the peak at this wavenumber [56,57]. According to reports, this peak also represents the interactions between free water molecules through hydrogen bonds [57]. Further in the spectrum, a doublet was observed at 2977 cm^{-1} and 2926 cm^{-1}. These peaks can be ascribed to the stretching vibrations of the aliphatic C-H groups due to various organic molecules, like carbohydrates, proteins, and a small amount of lipids in the wheat kernel. The control pasta sample exhibited a small peak at 1746 cm^{-1}, which is presumably due to the carbonyl

(C=O) stretching in starch, proteins (e.g., gluten), and sugars (e.g., fructose and glucose). Moving to the lower wavenumbers, two sharp peaks related to the amide I and the amide II bonds were detected at ~1646 cm^{-1} and ~1542 cm^{-1}, respectively. These peaks were due to C=O stretching and NH bending, respectively [55–57]. Lastly, in the fingerprint region, a shoulder peak was detected at 1148 cm^{-1} along with a sharp peak at 1016 cm^{-1}. The former peak can be assigned to the stretching vibrations of C-O and C-C bonds [57], whereas the latter can be ascribed to the vibrational modes within the amorphous phase of starch molecules [56,58]. Compared to the control pasta, the oleogel-containing pasta showed a shift in the doublet peaks (2977 cm^{-1} and 2926 cm^{-1}) to lower wavenumbers at 2924 cm^{-1} and 2856 cm^{-1}. These peaks indicate the presence of lipids in the pasta samples [56]. The shift towards the lower wave numbers can be associated with the structural modifications in the pasta samples due to the addition of oleogel. Furthermore, these samples showed a sharp peak at 1746 cm^{-1}, which could be attributed to the C=O stretching of esters (e.g., triglycerides) [57].

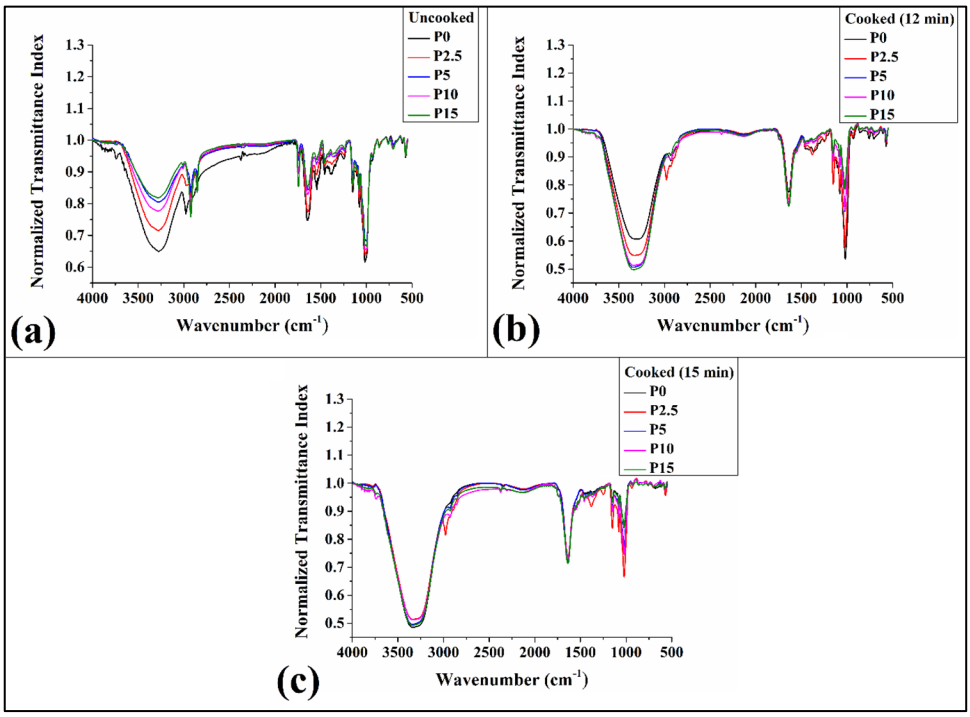

Figure 11. FTIR spectra of uncooked (**a**), 12 min (**b**), and 15 min (**c**) cooked pasta samples.

Figure 11b,c display the FTIR spectra of the cooked pasta samples. After cooking, the control sample (P0) revealed prominent peaks at 3311 cm^{-1}, 2920 cm^{-1}, 2850 cm^{-1}, 1744 cm^{-1}, 1638 cm^{-1}, 1385 cm^{-1}, 1150 cm^{-1}, 1081 cm^{-1}, and 1018 cm^{-1}. In comparison with the control sample, all the displayed oleogel-incorporated pasta samples showed similar peak intensities at similar wavenumbers. This could be attributable to the release of oleogel from pasta during cooking, which consequently reduces the amount of lipids in the samples. The leaching of the lipids was confirmed by the reduction in the peak intensity at 1744 cm^{-1} in the oleogel-containing cooked pasta samples compared to the uncooked ones. Interestingly, unlike the other pasta samples, P2.5 showed a peak shift of doublets (2920 cm^{-1} and 2850 cm^{-1}) to 2979 cm^{-1} and 2928 cm^{-1}. Overall, replacing water with oleogel resulted in changes in the lipid and water region, according to the observed changes in the spectra.

4. Conclusions

In this study, an attempt was made to develop whole wheat pasta by incorporating oleogel at different concentrations. Five samples were made by replacing water with

oleogels at concentrations of 2.5%, 5%, 10%, and 15%. The width, thickness, and colorimetric parameter analysis suggested significant differences in the oleogel-containing cooked pasta compared to the control sample. The colorimetric analysis revealed substantial differences in L*, a*, and b* values, indicating alterations in color attributes. The cooked pasta displayed lower L* values, higher a* values, and reduced WI values (except for P2.5). Furthermore, the YI readings escalated in P0, P5, and P10 with the incorporation of oleogel, leading to substantial color shifts (ΔE). Microscopic evaluation using a stereo zoom microscope and FESEM highlighted changes in the surface topology and the starch–gluten matrices, particularly in the samples with a higher oleogel content (P10 and P15), where the presence of black spots suggested the formation of starch–lipid complexes [32]. Post-cooking, an increase in porous structures was observed, which correlated with the oleogel content, due to the melting and leaching of oleogel from pasta. The hydrophobic character, which was attributable to the starch–lipid complexes, influenced the water absorption capacity (WAC), swelling index (SI), and moisture content. The samples with higher oleogel content exhibited lower WAC and SI and an overall lower moisture content. Interestingly, incorporating oleogel in the pasta samples led to an increase in dry matter content that reduced cooking loss and consequently increased its quality. Mechanical analysis of the pasta samples in the stress relaxation study revealed the greater intrinsic stability of the cooked pasta samples compared to the uncooked ones. Oleogel substitution also increased polymer network stability, which could increase the pasta samples' texture retention, shelf life, and consistency. Notably, the P10 sample stood out, and it demonstrated distinctive trends in texture properties, such as %SR, F_{max}, and work of penetration. Lastly, the IR spectroscopy of the pasta samples showed changes in the water and lipid regions after incorporating oleogel. Despite the predominantly ascending or descending trends in the various parameters, making it challenging to draw definitive conclusions regarding the most optimal oleogel concentration, the P10 sample exhibited unique texture properties compared to the other samples. In the future, this study could be expanded to assess the sample's nutrient profile and to conduct sensory evaluations. These additional analyses may contribute to the identification of the most optimal oleogel concentration among the various alternatives.

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